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Evaluation and measures to increase performance coefficient of hydrokinetic turbines

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ABSTRACT

In this study was presented the valid equations for energy conversion system from water currents analogous to wind power system. Hydrokinetic technology may be divided into two categories such as horizontal and vertical system. Application of the systems is possible to marine, and river currents. Each system has different performance coefficient. Hydrokinetic energy conversion systems shows lower power coefficient. The existing measures with the purpose of increasing of performance coefficient have been presented. Additional suggestions have been put forward. Future perspectives for application improvement and working fields of different kind have been given.

Contents

1. Introduction

All interested parties consent today to use renewable energies to cover the increasing energy deficit. Therefore, generating electricity from renewables is now one of the most strived topics for investigations [1]. Under renewable energies hydro, wind, photovoltaic (solar), biomass, geothermal energies can be enumerated [2]. Hydro and windpower seem to be optimum choices among the renewables available today [1]. Conventional hydroelectric plants harness the potential energy stored in large reservoirs by creating a hydraulic head differential which is converted to electrical energy. In stream, water current or kinetic energy turbines go one step further by simply utilizing the energy in the velocity of the water in the stream [3]. Energy can be extracted from the ocean and river currents by using submerged turbines, which are similar in function to wind turbines, capturing energy through the processes of hydrodynamic, rather than aerodynamic, lift or drag. Turbines can have either horizontal or vertical axes of rotation [4].

The use of kinetic energy of rivers can be considered as one of the first forms men invented to transform natural forces into mechanical work. The use of kinetic energy is considered to be an alternative or non-conventional form to generate electricity and has its source from a renewable energy supply. This technology is advanced in relation to environmental impacts, for it is not necessary to store potential energy in artificial lakes with the use of water dam, and so it consequently does not need to interfere with the natural course of rivers [5].

The category of water current turbine employed can be characterised by its rotational axis orientation with regard to the water flow direction. The axial flow water turbine has an axis of rotation parallel to the current direction and its rotor must be controlled to follow the current direction, in order to increase the power conversion efficiency. Otherwise, if the rotational axis is perpendicular to the current, the turbine operates whatever the flow direction. This category of turbine is known as Cross Flow Water Turbine. This type of turbines has several advantages, but the design

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and the prediction of their hydrodynamic behaviour are more complex [6].

Water current turbines extract energy from the fluid by reducing flow velocity. There is a theoretical limit to the percentage of kinetic energy that can be removed from the flowing fluid to the kinetic energy maximum available in fluid. This limit is known as Betz limit. Betz limit is 59.3% for a single and open actuator disc. Performance, C_P, or power coefficient is a measure of the fluid dynamic efficiency of the turbine and differs depending on manufacturer [7]. It became a common practice to use this limit for estimating the maximum efficiency of such turbines [8]. Performance coefficient takes different factors into account.

It is essential to take measures to improve the efficiency of the system. Many researchers are directed to this issue recently. The aim of this study is to present the hydrokinetic potential, to show the formation of the performance coefficient and to set and discuss the measures taken and to be taken to increase this ratio. Moreover,

Nomenclature

P	power (W)
ρ	density (kg/m^3)
A	area (m^2)
U	velocity (m/s)
T	thrust force (N)
$\dot{m}$	mass flow (kg/s)
p	pressure (pa)
a	interference factor
C_P	performance coefficient

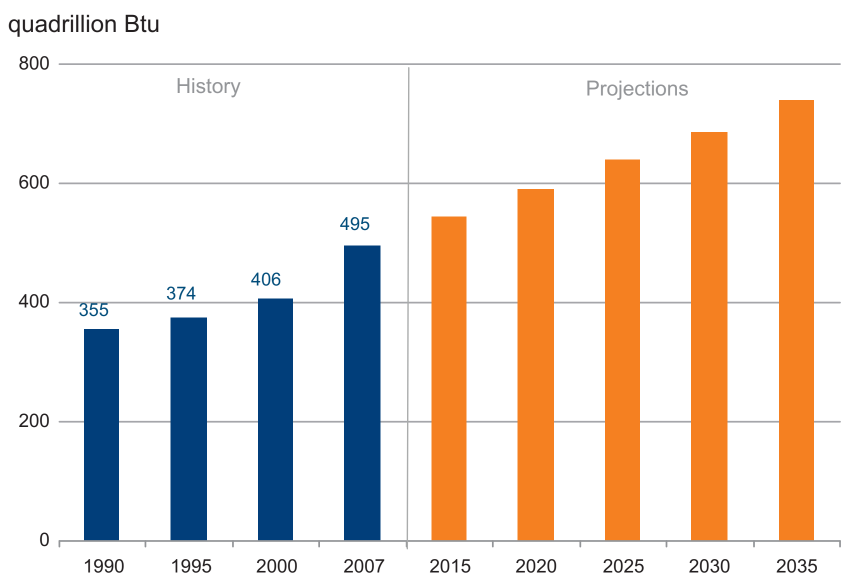

Fig. 1. World market energy consumption 1990–2035.

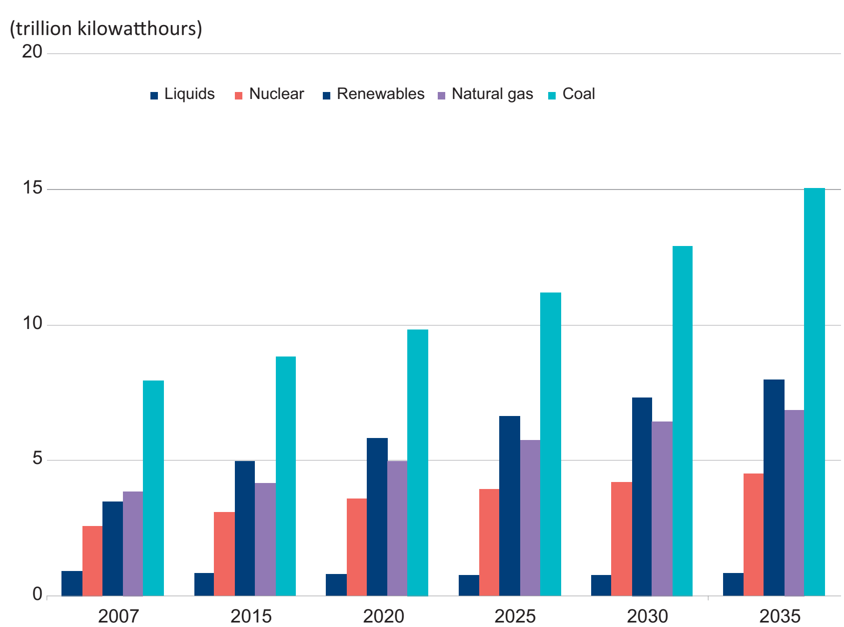

Fig. 2. World net electricity generation by fuel 1990–2035.

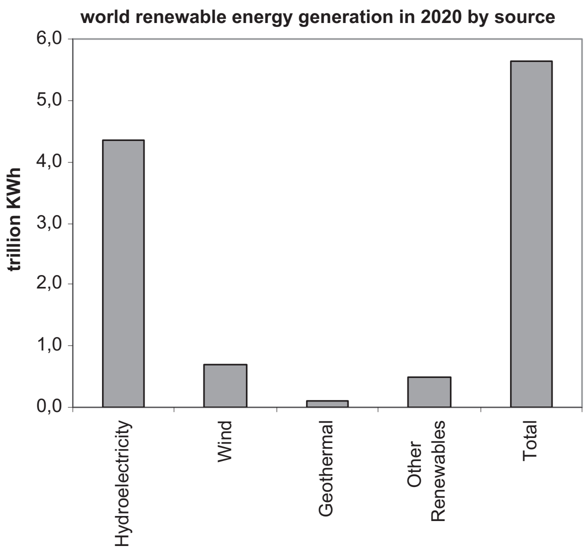

Fig. 3. World renewable energy generation in 2020 by source.

it aims to shed light on the precautions to be taken in river applications, and to introduce a new method for structural construction of vertical axis turbines with quided fixed-wing which is characterized by fixed inner blades. These inner blades are used to capture the water escaping from the rotating wings and to return it again. The introduced system promises to be much more efficient than the classical vertical axis turbines.

2. Hydrokinetic potential

Increasing energy demand, changing consumer habits, diminishing fossil resources and their environmentally harmful effects require usage of diversified and renewable energy sources. World energy consumption and future forecasts are presented in Fig. 1. World net electricity generation is shown in Fig. 2. Expectation of world renewable energy generation is given in Fig. 3. Hydrokinetic energy capacity forecast is presented in Fig. 4 [9].

Recent technological advancements and project-development initiatives clearly indicate a rejuvenated interest in the domain of hydrokinetic energy conversion [8]. Resource potential and technologies for capturing ocean and river current energy seem to be essential. Some environmental and economic impacts are associated with the technologies [4]. In 1996, a report to the European Commission suggested that the yearly potential for tidal energy in Europe was 48 TWh, most of which could be found around the UK [10,11]. The whole world energy potential is estimated to be 2.7 TW [12] and the exploitable part over the European shore is about 48 TWh, with 36 for UK and 10 for France. This energy could be a significant contribution to the European hydroelectric production of 580 TWh [13]. The U.S. Department of Energy has identified as much as 3400 MW of unexploited hydroenergy by small and potentially free-owing systems [14]. Additionally, small hydropower has been noted as a high potential source of energy internationally. Places such as the United Kingdom, Greece, Turkey, and India have already identified the source and they have performed initial supply analysis [15,16], whereas other regions such as Ghana and Brazil are identified as having high potential for this technology [17]. Utilizing these potential renewable resources gives a promising scenario for addressing the problem of the pending energy crisis we face as a global community [18]. Hydropower development must be preceded with vigilance though, as past forms have been proven harmful to the environment.

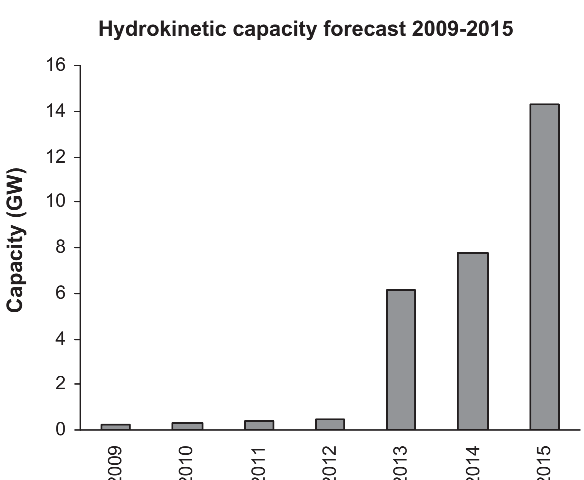

Fig. 4. Hydrokinetic energy capacity forecast 2009–2015.

The global tidal range energy potential is estimated to be about 200 TWh/y, about 1 TW being available at comparable shallow waters. Within the European Union, France and the UK have sufficiently high tidal ranges of over 10 m. Beyond the EU, Canada, the CIS, Argentina, Western Australia and Korea have potentially interesting sites. At present 3 tidal barrages operate as commercial power plants, amounting to a worldwide total of 260 MW of installed capacity. The potential for marine current turbines in Europe is estimated to exceed 12,000 MW of installed capacity. Locations with especially intense currents are found around the British Islands and Ireland, between the Channel Islands and France, in the Straits of Messina between Italy and Sicily and in various channels between the Greek Islands in the Aegean. Other large marine current resources can be found in regions such as South East Asia, both the east and west coasts of Canada and certainly in many other places around the globe that require further investigation. The UK has the major component of the EU resource at approximately 4.3 GW [19]. The mass of water carried by the Gulf Stream in the Atlantic Ocean at 380 North Latitude is 82 million m^3/s, which is many times greater than the water flow of all the Earth's rivers together [20].

3. Theory of hydrokinetic turbine and performance coefficient

Tidal and river stream energy technologies are in the early stages of development with various generating systems currently being researched. Many different basic turbine configurations have been reviewed in literature and their generating efficiency has been assessed. Supporting structures for the generating devices and the electrical power transmission system for shore connection have also been reviewed.

Most of the principals of this type of turbine are based upon wind turbines, as they work in a similar way.

During the quiet flow state, a column of wind upstream of the turbine with cross-sectional area A_1 of the turbine disc has kinetic energy passing unit time of [21]

$$P_0 = \frac{1}{2}(\rho A_1 U_0)U_0^2 = \frac{1}{2}\rho A_1 U_0^3 \qquad (1)$$

Water density depends weakly on salt content. Area A_1 is the rotor swept area. The analysis assumes a control volume, in which the control volume boundaries are the surface of a stream tube and two cross-sections of the stream tube, Fig. 5. The only flow is across the ends of the stream tube. The turbine is represented by a uniform 'actuator disc' which creates a discontinuity of pressure in the

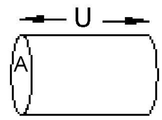

Fig. 5. Kinetic power in water stream.

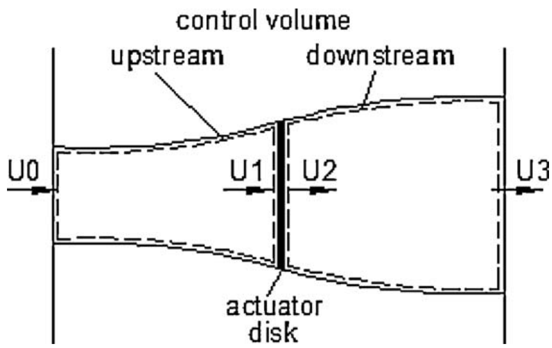

Fig. 6. Actuator disc model of a water current turbine.

stream tube of water flowing through it. The following assumptions were performed in this analysis [22]:

- no frictional drag;
- homogenous, incompressible, steady state fluid flow;
- an infinite number of blades;
- uniform thrust over the disc or rotor area;
- a non-rotating wake;
- the static pressure far upstream and far downstream of the rotor is equal to the undisturbed ambient static pressure.

The theory proceeds by considering supposed constant velocity water stream lines passing through and by the turbine in laminar flow, Fig. 6. Across the actuator disc, there is a change of pressure as energy being extracted and a consequent decrease in the linear momentum of the water [21]. From the applying the conversation of linear momentum to the control volume, the thrust is equal and opposite to the rate of change of momentum of the water stream.

$$T = U_0(\rho AU)_0 - U_3(\rho AU)_3 \tag{2}$$

The equation $\dot{m} = (\rho AU)_0 = (\rho AU)_3$ may be written for steady state flow. Therefore:

$$T = \dot{m}(U_0 - U_3) \tag{3}$$

The Bernoulli equation may be used on either side of the actuator disc. For the upstream side:

$$p_0 + \frac{1}{2}\rho U_0^2 = p_1 + \frac{1}{2}\rho U_1^2 \tag{4}$$

For the downstream:

$$p_2 + \frac{1}{2}\rho U_2^2 = p_3 + \frac{1}{2}\rho U_3^2 \tag{5}$$

The pressures p_0 and p_3 can be assumed equal, and the velocity ($U_1 = U_2$) on the both side of the disc remains the same.

Another expression of the thrust can be obtained from the difference of the forces on both side of the disc:

$$T = A_1(p_1 - p_2) \tag{6}$$

One can find the difference $p_2 - p_3$ by using Eqs. (3) and (4) and substitutes to Eq. (6), and then the following equation is obtained.

$$T = \frac{1}{2}\rho A_1(U_0^3 - U_3^2) \tag{7}$$

There are two different expressions available for thrust value. Equating these values from Eqs. (3) and (7) and recognizing that the mass of water flowing through the disc per unit time is given by

$$\dot{m} = \rho A_1 U_1 \tag{8}$$

Hence

$$U_1 = \frac{U_0 + U_3}{2} \tag{9}$$

That means, the water velocity at the rotor plane is the average of the upstream and downstream water speeds [22]. The water speed through the actuator disc cannot be less than half of the unperturbed water speed [21]. If one defines the interference factor, a, as the fractional decrease in water speed between the free stream and the rotor plane, then

$$a = \frac{U_0 - U_1}{U_0} \tag{10}$$

and

$$U_1 = (1 - a)U_0 \tag{11}$$

Using (9)

$$U_3 = (1 - 2a)U_0 \tag{12}$$

Power (P) can be obtained by water velocity time of the thrust value:

$$P = \frac{1}{2}\rho A_1(U_0^3 - U_3^2)U_1 = \frac{1}{2}\rho A_1 U_1(U_0 + U_3)(U_0 - U_3) \tag{13}$$

One substitutes U_1 and U_3 from Eqs. (11) and (12) into Eq. (13). Therefore:

$$P = \frac{1}{2}\rho A_2 U_0^3 4a(1 - a)^2 \tag{14}$$

If A_1 is replaced by A and U_1 is replaced by U, then:

$$P = \frac{1}{2}\rho AU^3 4a(1 - a)^2 \tag{15}$$

The performance coefficient is defined rotor power per power in the water. Hence

$$C_P = \frac{P}{(1/2)\rho AU^3} = 4a(1 - a)^2 \tag{16}$$

The derivatives of performance coefficient with respect to a and setting it equal to zero, gives the maximum C_P value of 0.59.

The theoretical maximum power available from the river and marine current is expressed by the equation above using a performance coefficient of 0.59, or 59% efficiency. But a small-scale river turbine has its own losses which will reduce the performance coefficient to around 0.10–0.25. The significant aspect to the equation is that the power increases in a cubed relationship to the velocity of the flow of water past the turbine. Therefore, it is important to find the best flow to get the best power output.

Laboratory tests and measured efficiencies of operating turbines often confirm that the Betz limit is too high for both hydraulic and wind plane turbines. In particular, comparative performance of various hydraulic turbines in free flows shown supports the thesis that the Betz limit highly overestimates the propeller capacity when used in the water. The same comparison leads to the conclusion that the three-dimensional helical turbine would be preferable to any plane propeller in free water flows. The nonconstrained helical turbine has exhibited an efficiency of 35 percent, for example, in well-documented hydraulic tests, and is superior to other known hydraulic turbomachines [23].

Hydro-kinetic turbines can be classified into two types. The first is the vertical-axis turbine, whose turning axis is perpendicular to stream flow; secondly, the axial turbine, whose rotational

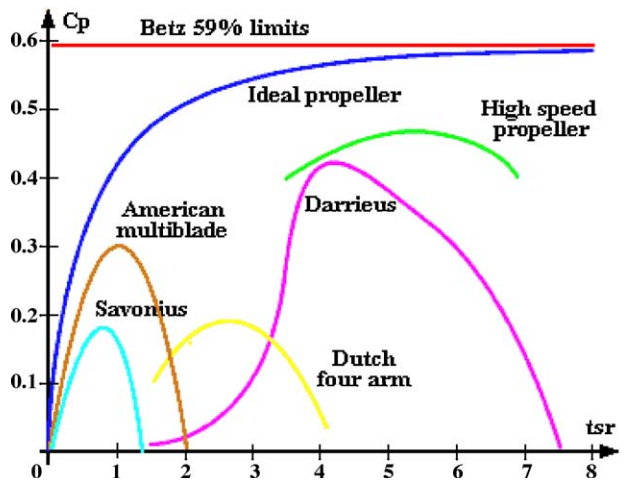

Fig. 7. Performance coefficient of different wind turbines.

axis follows the direction of flow. Vertical-axis turbines are preferable in situations, where flow direction changes, such as in tidal systems. These turbines are designed so that the direction of rotation remains the same regardless of the direction of flow. Vertical axis turbines can be classified in three categories such as Darrieus, H–Darrieus and helical. The Darrieus turbine was enthusiastically met by engineers and scientists in both wind and hydropower industries because of its simplicity and because the turbine allowed high speed to develop in slow fluids, maintaining a large passage area without substantially increasing its diameter [24,25]

The performance coefficients of different free flow turbines for wind application are depicted in Fig. 7 [26]. The Performance coefficient of Darrieus Savonius model turbine is given in Fig. 8 [27]. Variation of performance coefficient with TSR of H–Darrieus turbine is presented in Fig. 9 [28]. The maximum performance coefficient for helical turbines is 0.31 given by Gorlov [20]. The turbine efficiency $C_P = 0.35$ is found in most tests of the triple-helix turbine in free flow [29]. Performance coefficient of vertical axis wind turbine is presented in Fig. 10.

Since the design of a hydrokinetic turbine has basic differences compared to a typical wind/tidal turbine, performance features also vary in a unique manner. Knowledgebase in this field is limited and predicting the operational characteristics is also very important [30]. The minimum workable velocity of the river is about 0.8–1 m/s but preferably 1.3–1.5 m/s going up to a maximum of 3 m/s for the

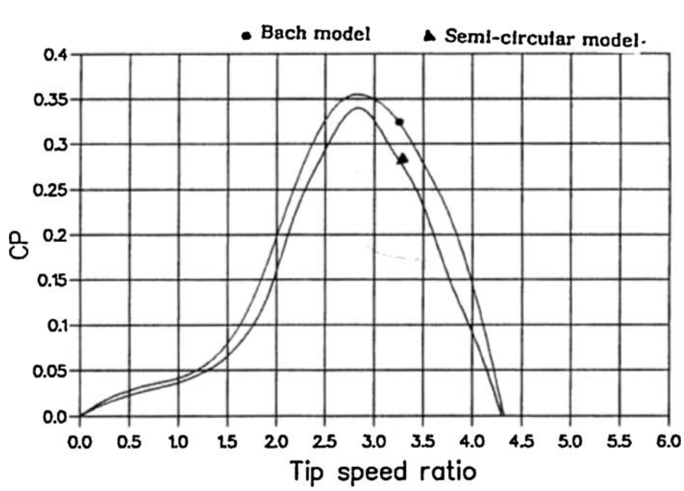

Fig. 8. Performance coefficient of Darreus Savonius model turbine.

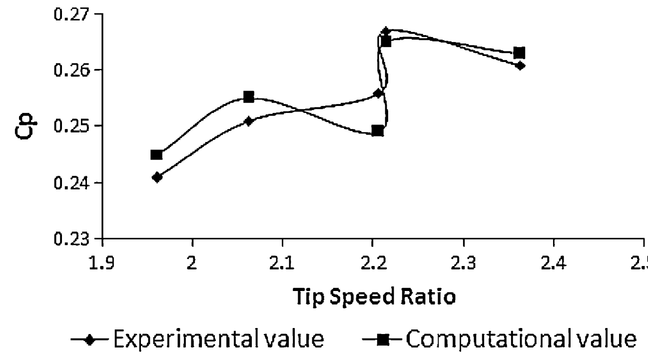

Fig. 9. Variation of performance coefficient with TSR of H–Darrieus turbine.

type of floating turbines. The engineering would need to be more substantial for higher river speeds [31].

4. Putting the theory into practice and measures for horizontal and vertical axis turbine

The conversion of hydrokinetic energy, which is available in Marine and river current, is possible due to horizontal and vertical axis hydrokinetic turbines [32–35]. Some of this technology has been used in wind energy conversion system for decades. Actually, the water hydrokinetic systems can be defined as wind turbines partially or completely submerged under water.

The providing of the theorical Betz limit is impossible in practice for unducted systems [36]. The value of performance coefficient (VPC) is required to follow a smooth curve in order to get the best energy efficiency at different water speeds. The maximum values for each type of turbines place in different water speeds. The VPC decreases further away from maximum velocity. Hence, it indicates lower values for a large part of river regimes. With innovation and improvement on turbine system may be target to reach a high VPC and quasi-smooth change of the curve in wide water speed range. While this target is achieved, the initial investment costs can be performed in inexpensive intervals. Therefore, improvement of simple and easy methods should be preferred. Thus, unexploided kinetic energy of the rivers and marine current can be rendered energy-productive. With the providing of environmentally benign, renewable, sustainable, and affordable energy source can be met increasing consumer requirements. Thus, more comfortable living standard can be prepared. This system seems to be implemented in very large capacities.

Generally, the measures to increase the energy obtained from the water currents can be divided into two categories. One of them

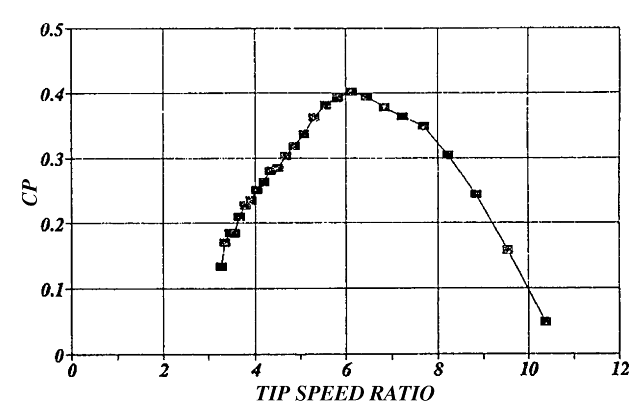

Fig. 10. Performance coefficient of vertical axis wind turbine.

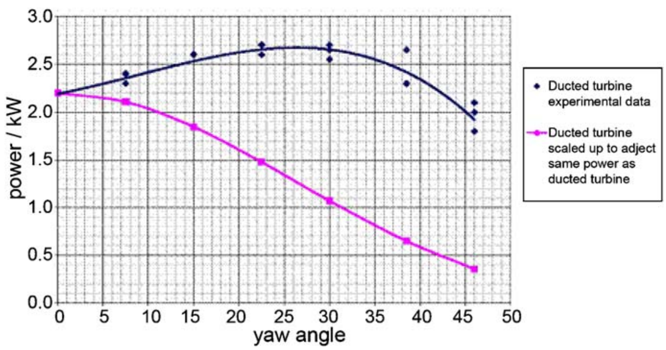

Fig. 11. Comparison of ducted and unducted turbines.

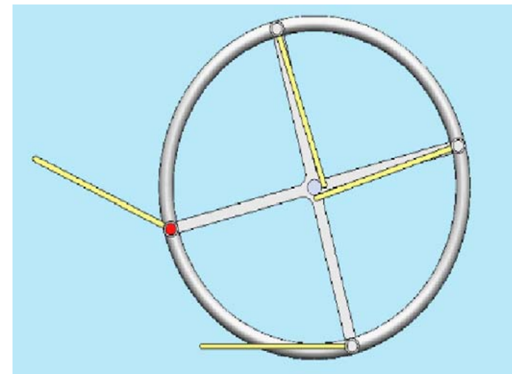

Fig. 13. Flip wing mechanism.

is the measure to increase the water current velocity. The suggestions for this purpose are given below:

- Assembly areas of the turbine system can be preferred in places where the land slopes or water current velocity are relatively higher.
- The water flow speed can be increased by creating of man-made channel, where the frictional resistance can be minimized. It is well known that river bed and sediment structure reduce the water flow velocity strongly.
- Increasing of water flow velocity at the inlet of the turbine is possible due to flow nozzle or ventury duct, which is applicated by lunar energy, Fig. 11 [37].

The other is the measure to increase the performance coefficient of the system. Analyses of the wind turbines, which achieved an advanced stage of development, show that their performance coefficient varies between 25 and 40%, and it gives the maximum value in a narrow water speed range. The system indicates relatively lower levels at the other speeds. Three different solutions may be used to increase of performance coefficient.

- The improvement of blade form and profile. The unique and original solution for water turbines should be investigated, the solutions for wind turbines cannot be sufficient and satisfactory.
- The realization of variable pitch blade structure, Fig. 12 [38].
- Usage of mechanism of flip-wing, Fig. 13 [39].
- Usage of fixed wing router.

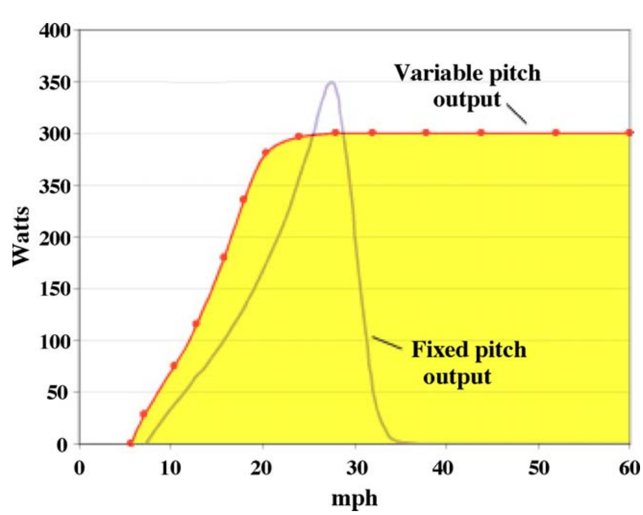

Fig. 12. Comparison of output curves.

Two different measures can be taken in horizontal hydrokinetic turbines for the increase of performance coefficient. First, adjustable wing angles exactly like Kaplan-Turbine can be performed to ensure optimum efficiency for different water speed and regimes. Secondly, with using ducted turbine (diffuser system such as ventury duct) can be achieved higher power rate [40]. This system can be applied everywhere if proper mounting location is available.

One of the three measures for vertical axis system differs from horizontal turbines. First, mechanism of flipwings can provide higher efficiency [41]. Initial investment of this system can be expensive and have shorter period of maintenance. Kirke and Lazauskas suggested the usage of variable pitch system for vertical axis Darrieus Turbine. Their work indicates that the performance coefficient can be increased above 0.4 [42]. However, the construction of variable pitch can lead to more expensive system costs. The third method is the addition of fixed-wing router on turbine body. Vertical turbine with fixed-wing router can be constructed easily. This system is expected to have an inexpensive investment cost and maintenance friendly structure compared to the others. All systems are under development. It can be expected that there will be rapid development and changes in hydrokinetic Technologies within the next few years.

5. Conclusion

The horizontal axis ducted turbine structure such as ventury duct indicates many advantages for increasing the performance coefficient in marine currents because of structural flow regimes. Author of this paper means, that the technology improvement expectation for ocean current will be in this way. After some time, the technology of variable pitch such as Kaplan-Turbine and ducted system should be combined.

River current is not able to form large systems because of uneven stream beds, shallow water level, and variable structure of river. In general, the river currents offer considerable less energy than ocean currents. Therefore, river energy conversion system should have more simple and easy solution in generators, control and speed increasing parts. Power transmission and generator of vertical axis turbine can be assembled above water level. That facilitates design, operation and maintenance of the system. One of the parameters, what influences the selection of generator, is the supply of stationary water flow regimes (constant velocity). The other parameter is using the place and target of the electricity. One can select an induction generator, which is simple, robust and inexpensive, due to supply of constant water speed. For this purpose, man-made channels may be created at the river edges. The initial investment costs can be reduced through these methods. The turbines can be placed into the channel one after another. The distance of the tur-

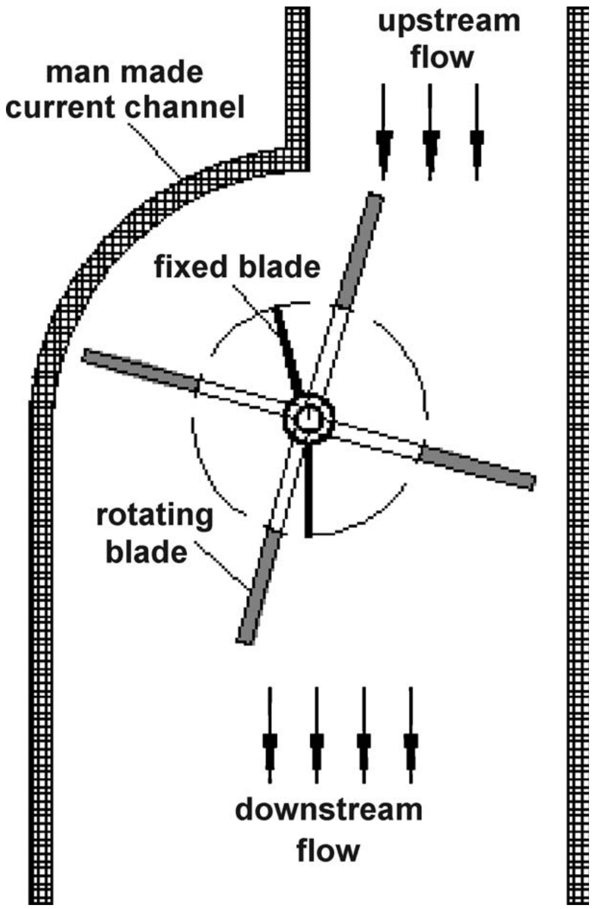

Fig. 14. Vertical axis turbine assembled in manmade channel.

bines should be selected carefully to ensure constant water speed at the system entrance.

Some of the wings are applied opposite torque to the rotation of the turbine. This is the reason of decreasing performance coefficient in vertical axis turbine. The measures to increase the performance coefficient should be simple and robust. For this purpose, the escaping water from the rotating wings, which creates useful torque to the other rotating wings, which can produce opposite torque, should be prevented. The author of this paper intended to construct a vertical axis turbine with fixed-wing router to achieve this target, Fig. 14. The studies of influences to the performance coefficient of the fixed-wing router have been started and they will be the topic of next paper.

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